Effective hygric and thermal parameters of historical masonry accessed on effective media theory principles

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Abstract

The experimental determination of hygric and thermal properties of two types of historical masonry stone materials and lime-metakaolin mortar is initially carried out. Nominally, water vapour transport properties, sorption isotherms, thermal conductivity with its dependence on rising moisture, and basic physical properties are measured using sophisticated laboratory methods. The researched materials are usually applied in the Czech territory for restoration and reconstruction of historical masonry and other structures. The measured material properties are subjected to a homogenization procedure, and the effective heat and moisture transport and storage parameters of a typical fragment of masonry are calculated. For the homogenization, the mixing model originally derived for application in dielectric studies is employed taking into account the theoretical bounds of investigated material parameters. The obtained data give information on hygrothermal performance of the modelled masonry fragment and can find use, for example, in the damage assessment of historical buildings using methods of computational analysis.

Keywords: hygric properties, thermal properties, historical stone masonry, argillite, sandstone, lime-based plaster, homogenization techniques.

1 Introduction

The hygrothermal behaviour of climatically exposed components and structures of historical buildings is related to the hygric, thermal, mechanical and other physical and chemical properties of inbuilt materials. Their knowledge constitutes necessary information for the understanding of the building
The damage assessment of historical masonry and other structures due to the negative effects of moisture and temperature can be carried out effectively by means of mathematical and computational modelling. In this way, the development of moisture and temperature fields with time can be obtained; this is crucial for a proper assessment of possible future damage [1]. Their prediction is a very important task when preserving historical bridges and buildings or insulating existing buildings and components. The moisture and temperature values can be then assigned to the mechanical properties and to the risk of consequent damage. For instance, Charles Bridge in Prague, Czech Republic, which was subjected to reconstruction work lately, is a typical example of extensive damage mostly brought about by temperature and moisture influences.

For the effective application of computational modelling to a buildings’ performance analysis, a complete knowledge of the properties of the applied materials as well as the initial and boundary conditions of the simulations is necessary. As the initial conditions for the hygric and thermal analysis, the moisture and temperature fields experimentally measured from the investigated structure can be used. The boundary conditions of the computer simulations are given by the climatic loading that can be simply adopted using meteorological data.

In engineering practice, simplified analyses of building structures’ behaviour are very often used. Here, in the computational simulations of heat and moisture transport processes, brick or stone masonry is often understood as a single material, the brick or stone itself. This simplification may work reasonably well when the properties of the brick or stone and the mortar are similar. However, this may not always be the case in some historical buildings, where low-quality mortars were often used [2]. On that account, the results of such calculations deviate from the real state of the buildings, and cannot be effectively used for assessing some appropriate materials’ damage and problems in hygrothermal behaviour. Therefore, a solution of this problem must be found in order to improve the accuracy and reliability of computational modelling of building structures performance.

There are two ways of meeting the above given requirements for reliability and accuracy in computational simulations of heat and moisture transport. The first possibility is the use of sophisticated simulation tools that allow discretization of the studied structure with such a resolution, that all the properties of inbuilt materials can be assigned values corresponding to specific places of the structure. Although this procedure is generally correct, it is too complex and sophisticated for wider application in engineering practice, especially in the case of conservationists of historical buildings who are usually well informed on materials’ problems without knowledge of computational modelling methods.

The second, and probably the most straightforward way to solve the problem of variations in the properties of the particular components of masonry is the utilization of the effective media theory. This procedure is introduced in
the presented work as an effective tool for the simplification of computational modelling of transport processes in the masonry. The application of homogenization principles produces the macroscopic equations which may be used when analyzing the masonry as a whole. In these equations, the effective parameters are used instead of the parameters of the brick or stone.

It should be quite apparent that the homogenization process cannot be carried out without the exact knowledge of the properties of all materials constituting the masonry and of the amount of each material in the analyzed wall. Therefore, the experimental measurement of all the material parameters characterising the process of heat and moisture transport and accumulation in inbuilt masonry materials is first necessary. These data are then introduced in the mixing models based on effective media theory, and the effective thermal and hygric parameters of the whole masonry can be calculated.

2  Studied materials

Two types of stones that were often used in Czech region in the past as bearing masonry materials are analysed together with lime-based mortar with pozzolana admixture.

Many historical buildings in the Czech Republic were built using similar kinds of sandstone. Siliceous raw-grained sandstone was usually used for historical architectural constructions (walls, portals, window frames) for its strength. Ornamental parts of the architecture (gothic flowers, romantic shells) and sculptures (from the Romanesque period up to now) were made of fine-grained calcite-argillaceous sandstone. In this work, sandstone from Mšené-lázně quarry, Czech Republic, is chosen. It is fine-grained psamitic equigranular rock, about 95% of which is made up of suboval quartz clasts. Other mineral grains are present only as minorities (tourmaline, epidote, muscovite and zircone). Quartz grains reach up to 0.1 mm in diameter, but those of muscovite are larger, up to 0.3 mm [3]. The matrix is formed by clay minerals (mainly kaolinite).

Also the argillite was very popular material in historical architecture. It was used for sacral as well as for secular buildings, flagstone pavements, roof slabs, and facing. The studied argillite is coming from quarry Džbán, Czech Republic. Its main constituents are illite, calcite, minerals on the basis of SiO₂ having granularity 0.3–0.15 mm, feldspar, and mica, whereas rigid materials form 40–60% of argillite volume.

Within the reconstruction of historical buildings, renewal and restoration of interior and exterior plasters and mortars is often carried out. From the point of view of a historian, it is not acceptable to use lime-cement mortars in Romanesque, Gothic, Renaissance, and Baroque buildings. However, the pure lime-based plaster does not exhibit sufficient resistivity against moisture action. On that account, proper hydraulic admixtures must be used that enhance the durability of mortars. These materials must have similar composition as the historical materials and they have to be applicable by the original technological processes.
As the chemical analyses of many plasters from historical buildings show, the external plasters from past centuries that are preserved until today contain products formed by lime reaction with pozzolanic or hydraulic admixtures. Pozzolanic admixtures appeared to have a positive effect on properties of lime binder in the past. On that account, a lime-based mortar with metakaolin addition as pozzolana admixture was chosen. The composition of the lime-metakaolin plaster was as follows: hydrated lime – 400 g, metakaolin – 80 g, natural quartz sand with continuous granulometry 0 to 2 mm – 1 440 g, and water – 480 g.

3 Experimental methods

Basic material properties of all tested materials were determined at first. Bulk density and matrix density were measured using the gravimetric method and helium pycnometry, and then the total open porosity was calculated. The samples’ dimensions for these measurements were 40×40×20 mm³.

For the determination of water vapour transmission properties, the cup method was applied, according to the European standard EN ISO 12571 [5]. The measurements were carried out under steady state isothermal conditions. The dry cup arrangement was used in the experiment. Here, the sealed cup with the studied material sample containing burnt CaCl₂ (0% relative humidity) was placed in a controlled climatic chamber at 25±0.5°C and 50% relative humidity and it was weighed periodically. The circular samples had a diameter of 95 mm and a thickness of 20 mm. The steady state values of mass gain were utilized for the determination of the water vapour permeability. On the basis of measured water vapour permeability, the water vapour diffusion coefficient and water vapour resistance factor were calculated using the simple formulas given in [6, 7].

For the determination of moisture diffusivity as function of moisture, the moisture profiles were measured at first. The measurements were carried out on samples having dimensions of 40×20×300 mm³ in 1-D experimental arrangement of water transport. The moisture content at a specific position in the sample was measured by the capacitance technique calibrated by the gravimetric method. The moisture dependent moisture diffusivity was then calculated using the inverse analysis of the measured moisture profiles by means of the Boltzmann-Matano treatment [8].

In the sorption isotherm measurement, the samples were placed into the desiccators with different salt solutions to simulate different values of relative humidity. The mass of samples was measured in specified periods of time until a steady state value of mass was achieved. Then, the volumetric moisture content was calculated and the sorption isotherm of each tested material was plotted.

The thermal conductivity as the main parameter of heat transport was determined using the commercial device ISOMET 2104 (Applied Precision, Ltd.). ISOMET 2104 is a multifunctional instrument for measuring thermo-physical parameters which is based on the application of an impulse technique and is equipped with various types of optional probes [9]. Thermal conductivity
was measured in the moisture range from the dry state to full water saturation on the 70 mm cubes.

4 Effective media theory and homogenization techniques

The application of the effective media theory allows the determination of the properties of the whole masonry or building structure instead of the parameters of the particular inbuilt materials. In terms of effective media theory, the final composite structure (in our case stone masonry wall) can be considered basically as a mixture of walling blocks and mortar. In more precise calculations, each of these materials can be further considered as a mixture of three phases, namely solid, liquid and gaseous phase (in four phase systems, the effect of bound water can be included) that form their matrix and porous space. There are two basic approaches that can be applied for determination of thermal and hygric properties of the stone masonry. The first possibility is to apply homogenization techniques on the moisture dependent material data of the materials encountered in the masonry. This simplified procedure was used in this work. The second possibility is based on the complete knowledge of material properties of the particular components forming the porous body of the structure (dry stone, dry mortar, free water, bound water and air). From the properties of particular components and their volumetric fractions the effective properties of the stone masonry can be assessed.

On the basis of previous experience with application of homogenization techniques, the original Lichtenecker’s formula [10] was chosen for the calculations performed in the presented work; this formula was proved to be satisfactory for the evaluation of moisture dependent thermal and hygric properties of porous building materials [11]. Also the application of four phase models looks promising. However, in case of the masonry studied in this work, the determination of the amount of bound water represents a very complex problem.

The Lichtenecker’s equation adjusted for the studied masonry wall assumes that the effective hygric and thermal parameter of the considered material satisfies the equation

$$p_{\text{eff}}^k = f_b p_b^k + f_m p_m^k,$$

where \(p_{\text{eff}}\) is the calculated effective parameter of masonry, \(f_b\) the volumetric fraction of walling blocks in masonry, \(f_m\) the volumetric fraction of mortar, \(p_b\) the measured material parameter of walling block, \(p_m\) the measured parameter of mortar, and \(k\) is a free parameter describing basically the path from the anisotropy at \(k = -1.0\) to another anisotropy at \(k = 1.0\). However, the Lichtenecker’s equation may also be applied for isotropic materials. On the basis of previous experience, the value of the parameter \(k = 0\) was used.

The effective parameters of a multi-phase material cannot exceed the bounds given by the parameters of particular fractions of its constituents. Here, the Wiener bounds according to the Wiener’s original work were used [10, 11]. These bounds can be expressed by the following relations.
where eqn (2) represents the lower limit and eqn (3) the upper limit of the investigated effective material parameter ($f_i$ is the volumetric fraction of the particular phase, in our case argillite, sandstone and mortar), $p_i$ its material parameter).

5 Studied masonry

For the application of the homogenization theory for the evaluation of the effective hygric and thermal parameters of masonry, a typical fragment of the wall was constructed in a simplified manner, similar to common brick masonry as shown in Figure 1.

![Scheme of the reference masonry wall (dimensions in mm).](image)

Using this scheme, the volumetric fractions of the particular materials in the wall were calculated. The volumetric fraction of walling materials is equal to 0.824, whereas the volumetric participation of mortar is 0.176. Through the calculations, the effective parameters of two different walls were assessed. The studied walls always consisted of lime based metakaolin mortar, and of one walling material, nominally sandstone or argillite.
6 Results and discussion

The basic properties of all tested materials are summarized in table 1. Each result represents the average of five measured values. All the studied materials have shown high porosity; this is a very positive factor from the point of view of their presumed application in reconstruction of historical buildings.

The water vapour transmission properties of masonry materials are presented in table 2. Very low values of the water vapour resistance factor can be systematically seen; this is again a very promising finding for the application of all tested materials in historical masonry. Since a historical masonry usually exhibits increased moisture content, it is necessary to apply within the reconstruction processes such materials that will allow moisture evaporation from the renovated structures within the warm periods of the year.

| Table 1: Basic material properties of masonry materials. |
|---------------------------------|-----------------|-----------------|-----------------|
| material                        | bulk density (kg/m$^3$) | matrix density (kg/m$^3$) | total open porosity (–) |
| sandstone                       | 1807            | 2627            | 0.31            |
| argillite                       | 1353            | 2325            | 0.39            |
| lime-metakaolin mortar          | 1690            | 2620            | 0.35            |

| Table 2: Water vapour transmission properties of masonry materials. |
|---------------------------------|-----------------|-----------------|-----------------|
| material                        | dry cup arrangement, 0–50% |
|                                 | water vapour permeability (s) | water vapour diffusion coefficient (m$^2$/s) | water vapour resistance factor (–) |
| sandstone                       | 2.4E-11          | 3.3E-06          | 7.0             |
| argillite                       | 2.9E-11          | 4.1E-06          | 5.7             |
| lime-metakaolin mortar          | 1.8E-11          | 2.5E-6           | 10.1            |

| Table 3a: Water vapour transmission properties of stone masonry. |
|---------------------------------|-----------------|-----------------|-----------------|
| Sandstone wall – homogenization, dry cup arrangement – 0–50% RH |
|                                 | water vapour permeability (s) | water vapour diffusion coefficient (m$^2$/s) | water vapour resistance factor (–) |
| Wiener’s lower bound            | 2.29E-11          | 3.11E-06          | 7.40            |
| Wiener’s upper bound            | 2.24E-11          | 3.05E-06          | 7.55            |
| Lichtenecker model, k=0         | 2.27E-11          | 3.08E-06          | 7.47            |
The effective diffusion parameters of the studied stone masonry, calculated on homogenization principles, are presented in tables 3a and 3b. For verification of the calculated results, also the limiting bounds of effective parameters are presented. Looking at the obtained data of water vapour transmission properties, it can be seen that all the effective parameters lie between the Wiener’s bounds; this basically confirms their validity.

Table 3b: Water vapour transmission properties of stone masonry.

<table>
<thead>
<tr>
<th>Argillite wall – homogenization, wet cup arrangement – 0–50% RH</th>
<th>water vapour permeability (s)</th>
<th>water vapour diffusion coefficient (m²/s)</th>
<th>water vapour resistance factor (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wiener’s lower bound</td>
<td>2.74E-11</td>
<td>3.73E-06</td>
<td>6.17</td>
</tr>
<tr>
<td>Wiener’s upper bound</td>
<td>2.61E-11</td>
<td>3.55E-06</td>
<td>6.47</td>
</tr>
<tr>
<td>Lichtenecker model, k=0</td>
<td>2.69E-11</td>
<td>3.65E-06</td>
<td>6.30</td>
</tr>
</tbody>
</table>

The effective moisture diffusivity as function of moisture content is given in figs. 2 and 3, which show the high dependence of this moisture transport parameter on moisture content. This materials’ behaviour significantly affects the hygrothermal performance and consequently the durability. Sandstone systematically exhibits the highest moisture diffusivity. Its highly porous structure formed by high radius pores allows fast liquid moisture transport in comparison with argillite that is also characterised by high total open porosity, but its pore size is much smaller and structure more fine-grained.

Figure 2: Effective moisture diffusivity of sandstone masonry.
The calculated effective sorption isotherms of the studied masonry are given in figs. 4 and 5. Typically, the highest capacity for water vapour adsorption can be observed in lime-metakaolin mortar. However, in the hygroscopic moisture range, the highest values of adsorbed moisture were measured in argillite. The data obtained for sandstone were systematically the lowest.

Figure 3: Effective moisture diffusivity of argillite masonry.

Figure 4: Effective sorption isotherm of sandstone masonry.
The measured and calculated thermal conductivity of all studied materials and the two types of masonry is presented in figs. 6 and 7. The variation of the effective thermal conductivity with moisture content is systematically within the range of Wiener’s bounds; this basically proves the reliability of the applied homogenization technique.

Figure 5: Effective sorption isotherm of argillite masonry.

Figure 6: Effective thermal conductivity of sandstone wall.
Conclusions

An example of application of the homogenization technique for the determination of hygric and thermal parameters of stone masonry was introduced in this paper. The obtained results indicate that the Lichtenecker’s equation may be successfully used for such a type of applications. Nevertheless, there is still an unexplored task to verify the reliability of the applied homogenization model by laboratory experiments that should confirm or contradict the presented results.

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References


